Elemental Composition of the January 6, 1997, CME

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Abstract. Using solar wind particle data from the CELIAS/MTOF sensor on the SOHO mission, we studied the abundance of the elements O, Ne, Mg, Si, S, Ca, and Fe for the time period around the January 6, 1997, coronal mass ejection event (CME). In the interstream and coronal hole regions before and after this event we found elemental abundances consistent with the expected abundance patterns of the respective flow regimes. However, during the passage of the CME and during the passage of the erupted filament, which followed the CME, we found that the elemental composition differed markedly from the interstream and coronal hole regions before and after this event. During the passage of the CME and the passage of the erupted filament we found a mass-dependent element fractionation, with a monotonic increase toward heavier elements. We observed Si/O and Fe/O abundance ratios of about one half during these time periods, which is significantly higher than for typical solar wind.

Introduction

In this paper we present the first analysis of the elemental composition of the plasma associated with the coronal mass ejection (CME) which originated on January 6, 1997, on the solar surface and arrived at the SOHO spacecraft on January 10, 1997, at 04:11 UT. Approximately 30 minutes after the CME reached the SOHO spacecraft, it arrived at the location of the WIND spacecraft. From the WIND measurements it has been concluded that this CME falls into the class of magnetic cloud events [*Burlaga*, 1997]. It has been found earlier that near 1 AU about a third of all CMEs in the ecliptic plane are magnetic cloud events [*Gosling*, 1990].

The CME was slightly faster than the preceding solar wind and created a shock followed by a compression region. The shock was observed on SOHO on January 10, 1997, at 00:22 UT. The CME was followed by coronal hole type solar wind, which arrived at the position of the SOHO spacecraft on January 11 at 06:56 UT. Just before the arrival of the coronal hole, a pronounced increase in the proton density was observed which was attributed to an erupting filament [*Burlaga*, 1997]. Based on a complete set of solar wind plasma data (particles and magnetic field) available from the WIND spacecraft, the times and durations of the different phases of this event have been identified for the location of the WIND spacecraft [*Burlaga*, 1997].

We measured the solar wind plasma parameters—namely the solar wind speed, thermal speed, proton density, and N/S solar wind flow angle—with the proton monitor (PM), which is part of the CELIAS instrument. Using these solar wind plasma parameters, together with the information from the WIND spacecraft, the times of the passages of the shock, the CME, the filament, and the coronal hole associated solar wind were identified. The measured solar wind plasma parameters are shown in Figure 1 for the investigated time interval around the CME event. Due to saturation of the PM, the proton density spike from the filament eruption could not be measured correctly. WIND/SWE results indicate that the proton density was about $120 cm^{-3}$ in the spike resulting from the filament eruption, a value which is about a factor of ten above typical proton densities in slow solar wind.

The chosen time period offers a good opportunity to compare the elemental composition of the plasma during the CME passage with the two forms of *regular* solar wind composition, originating from the streamer belt (also called interstream or slow solar wind) which preceded the CME event, and with solar wind originating from a coronal hole (also called fast solar wind) following the CME event. The measurements were taken with the MTOF sensor (Mass Time-of-Flight) of the CELIAS (Charge, Element, and Isotope Analysis System) instrument on the SOHO spacecraft [*Hovestadt et al.*, 1995], which is located at the L1 libration point between Earth and Sun. The MTOF sensor is an isochronous time-of-flight (TOF) mass spectrometer utilizing the carbon foil technique, combined with an electrostatic entrance system. The entrance system allows ions to enter the sensor in a large energy range (only discriminating against protons, and partly against alpha particles) and through a wide angular acceptance cone. The MTOF sensor

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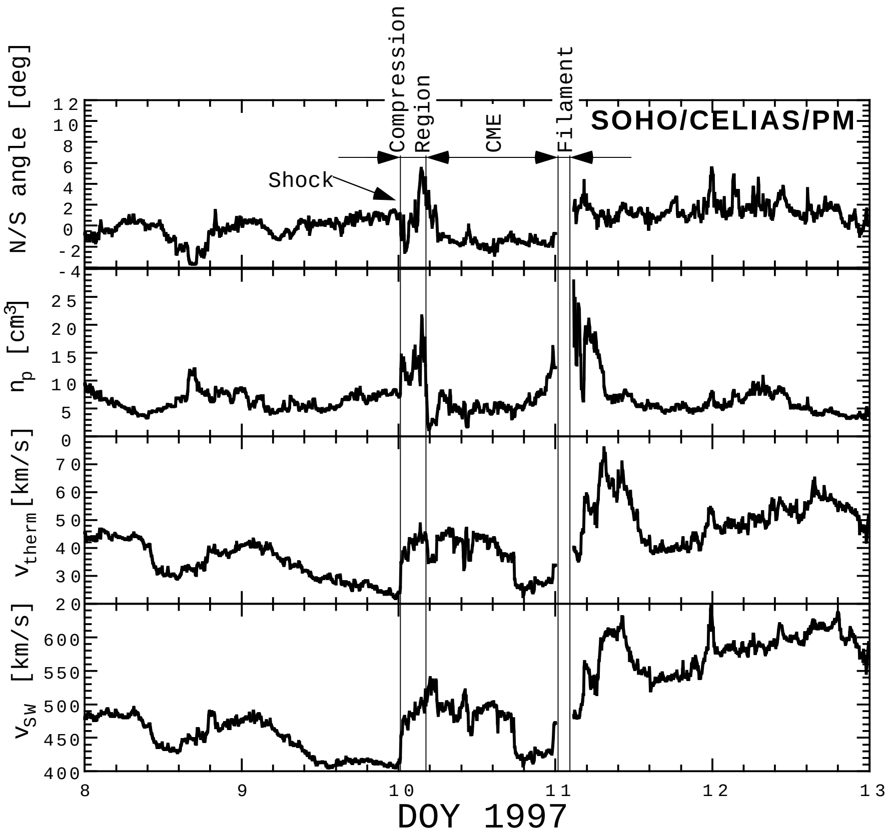

Figure 1. Solar wind plasma parameters as they are measured with the Proton Monitor, a sensor of the CELIAS instrument on SOHO, are shown for the investigated time period.

determines the mass of incoming ions with high resolution, sufficient to identify many isotopes and rare elements in the solar wind.

Data Analysis

From the ions recorded with the MTOF sensor, the CELIAS data processing unit accumulates time-of-flight (TOF) spectra for 5 minutes which then are transmitted to ground. In this study we evaluated the elements O, Ne, Mg, Si, S, Ca, and Fe. Mass peaks for the different elements were extracted from each of the transmitted TOF spectra. Subsequently, the overall efficiency of the MTOF sensor was calculated for each element and for each accumulation interval. To obtain particle fluxes for the chosen elements, the instrument response of the MTOF sensor comprising the transmission of the entrance system and the response of the isochronous TOF mass spectrometer, was taken into account in great detail. The actual solar wind plasma parameters, which were measured by the PM (see Figure 1), are needed as input parameters for the instrument response of the MTOF sensor. The precision of the determination of the solar wind plasma parameters with the PM is quite accurate [*Ipavich et al.*, 1997] and better than required for the determination of densities with the MTOF sensor. Another input parameter needed for the determination of the MTOF instrument response, in particular for the determination of the transmission of the entrance system, is the charge state distribution of each element for each accumulation interval. Since the MTOF sensor determines only the mass of the incoming ion, but not its charge, we derived the so-called freeze-in temperature from a simple model using only the solar wind velocity. From the freeze-in temperature we obtained charge distributions for each element by assuming an ionization equilibrium in the corona and by applying ionization and recombination rates for electronic collisions from *Arnaud* and co-workers [*Arnaud and Rothenflug*, 1985; *Arnaud and Raymond*, 1992]. The application of the instrument function to the measured data yielded preliminary densities for the different elements. We extensively checked if the instrument function introduces a mass bias, but so far we did not find such an effect in the data analysis.

The MTOF instrument settings are cycled in a six-step sequence, optimized to cover a broad range of solar wind conditions. The stepping sequence includes two voltage settings for the entrance system and three values for the potential difference between the entrance system and the TOF mass spectrometer (negative, zero, and positive potential difference). For the present analysis only the steps with negative or zero potential difference have been used. In principle a time resolution of five minutes, the dwell time for each step, can be obtained if the sensitivity of the MTOF sensor is high enough for the particular element considered. For typical solar wind conditions and for the more abundant elements in the solar wind, it is indeed possible to derive densities with such a high time resolution, as will be shown later in this paper.

Results and Discussion

Preliminary densities derived from the measured data for the elements O, Ne, Mg, Si, S, Ca, and Fe are shown in Figure 2 for the selected time period around the CME event, with a time resolution of 5 minutes. No smoothing of the

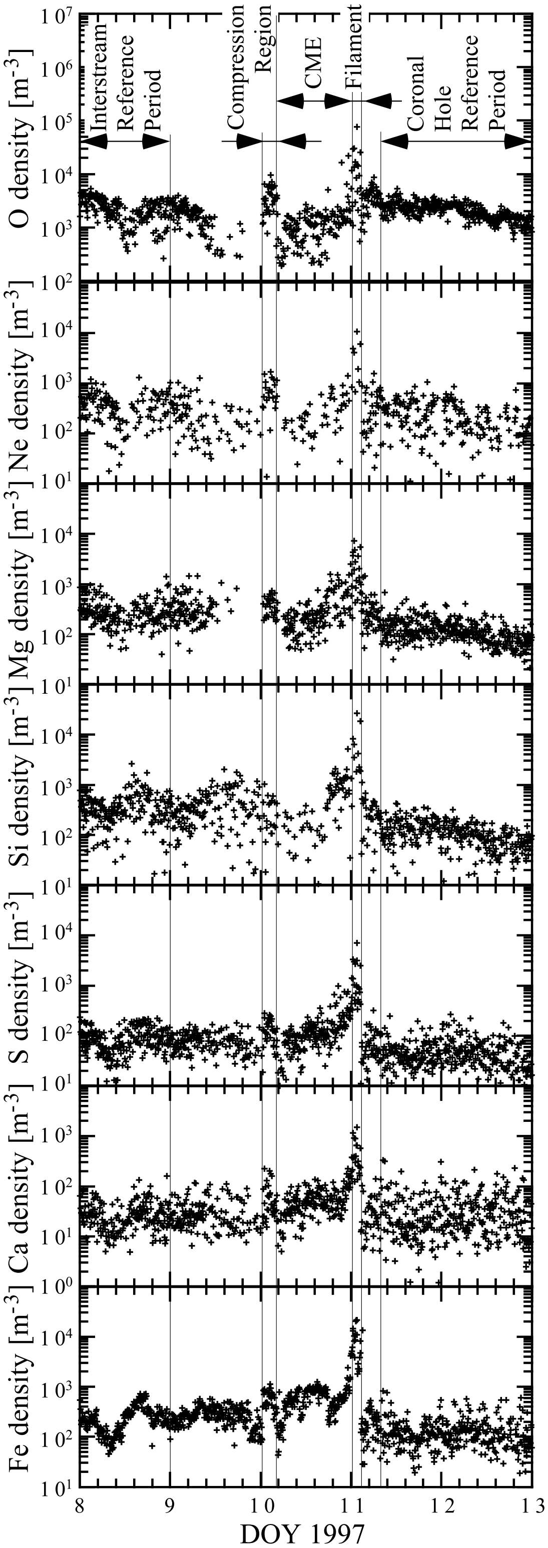

Figure 2. Densities for the different elements for the time period around the CME event derived from the CELIAS/MTOF sensor. Each data point represents a measurement of 5 minutes. No smoothing of the data has been applied.

data has been applied. What already is evident from Figure 1 without detailed analysis is that the compression region (DOY 10, 1997 from 00:36 UT until 04:24 UT) after the shock exhibits larger densities than the preceding inter-

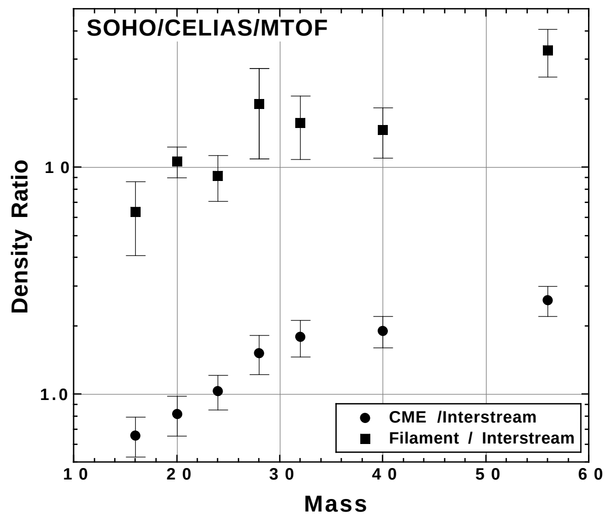

Figure 3. Density ratios for the different elements evaluated for the CME and the filament. Error bars are one-sigma wide and include statistical and instrumental errors.

stream solar wind (with DOY denoting the day of year). For the filament eruption (DOY 11, 1997 from 00:22 UT until 02:27 UT), we found a substantial increase in density during its passage. The time periods for the compression region after the shock, the CME (DOY 10, 1997 from 04:24 UT until DOY 11 00:22 UT) and the filament are indicated by vertical bars in Figure 2. To derive a reference density for the interstream regime, the data accumulated during DOY 8, 1997, were evaluated. For the reference density in the coronal hole associated solar wind, data from the time period after the stream interface (DOY 11, 1997, 06:22 UT) until the end of DOY 12 were evaluated. The stream interface was identified according to *Burlaga* [1974] through a decrease in proton density by a factor of about two compared to the density in the preceding interstream regime, and an accompanying two-fold increase in kinetic temperature. For the two reference periods we find that the abundance ratios relative to oxygen agree with published data of interstream and coronal hole type solar wind [*von Steiger et al.*, 1995].

In the compression region after the shock and before the CME, the densities of all elements increased by a factor of about two compared to their reference densities in the interstream region. The proton density, measured independently by the PM, also goes up by a factor of two during this time period. No mass dependence was found for the composition in the compression region. Similarly, the abundance ratios relative to oxygen clearly showed that the composition of the compression region resembled that of the preceding interstream solar wind regime, which is of course what one would expect for compressed solar wind following a shock.

For the CME passage we observed a markedly different composition compared to the interstream solar wind as well as compared to the coronal hole solar wind. We found a mass-dependent element fractionation in the sense that the lower mass elements were depleted and the heavier elements were enriched compared to their interstream reference densities. The oxygen density was only a factor of 0.66 ± 0.13 of its interstream value, the magnesium density remained at its value of 1.0 ± 0.2, and the iron density went up by a factor of 2.6 ± 0.4. Figure 3 shows the densities for the CME plasma compared to the reference density of the interstream regime. Looking at the elemental abundance ratios with respect to oxygen, we also found a clear correlation with the mass of the element considered. For the Ne/O abundance ratio an enrichment of a factor of 1.2 ± 0.2 compared to its interstream abundance ratio was found. For higher masses, the enrichment then increased monotonically up to a factor of 4.0 ± 0.6 for the Fe/O abundance ratio. For the CME plasma a Si/O abundance ratio of 0.43 ± 0.14 and a Fe/O abundance ratio of 0.42 ± 0.11 were found. No correlation was found between the abundance ratio with respect to oxygen and the first ionization potential (FIP) of the elements.

In the erupted filament the densities of all elements increased dramatically compared to their interstream values. A similar increase in density has also been observed for the protons [*Burlaga*, 1997]. Again we observed a clear mass dependence such as was found for the CME period (see Figure 3). For the O density we observed an increase by a factor of 6.5 ± 2.1 compared to its interstream reference density. On the high mass side we observed an increase by a factor of 19 ± 8 and 33 ± 7 for the Si and Fe densities, respectively, compared to their interstream reference densities. The mass dependence is also seen in the abundance ratio with respect to oxygen. For the filament plasma a Si/O ratio of 0.49 ± 0.25 and a Fe/O ratio of 0.53 ± 0.21 were found. Again, the increase in density cannot be correlated with the FIP.

In order to explain the unusual composition we found for the CME and the filament plasma we could envisage a bubble of material, the precursor of the CME and the erupting filament, residing on the solar surface where matter boils off from the bubble. Given the gravitational field of the Sun, lighter elements would be lost more easily than heavier ones and a mass-dependent change of composition would result if the bubble was reasonably isolated for a sufficiently long time on the solar surface. Once this bubble is released into space in the form of a CME or an erupting filament, it will carry with it the altered compositional information as observed in our data. Another explanation for the unusual composition could be fractionation by selective acceleration after the release of the bubble. The mass-dependence we found for the elemental abundance during the CME and during the filament eruption could as well be interpreted as a mass-per-charge dependence. Inferring the charge from the type of solar wind (since MTOF determines only the mass of ions), we also obtained a monotonic function for the increase of the elemental abundance with mass-per-charge during these time periods. ^{3}He-rich flares, i.e. impulsive flares, usually also show enhancements of heavy elements, with Fe/O abundance ratios up to one [*Meyer*, 1985; *Reames*, 1992]. This enhancement is monotonic with mass, and is also called *mass bias*, and results from the ion acceleration process that depends on the mass-per-charge of an ion as well as its velocity. However, whether the low energies (typically $1 keV/nuc$) of the particles we observed is sufficient to achieve the observed change in composition due to fractionation in the acceleration process remains to be demonstrated.

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